A Gaseous Energy Absorber for Ionization Cooling of Muon Beams

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Summary

The case is made for an ionization-cooling channel using low-temperature, high-pressure gaseous hydrogen or helium as a continuous energy absorber. Recent lattice designs with low-β regions that are continuous along the length of the channel encourage this approach. The gas and the RF cavities can be operated at the same low temperature to improve RF efficiency and to provide gas cooling of the Be windows or tubes of the closed-cell RF cavities. A gaseous absorber should improve ionization-cooling efficiency by eliminating the high-*Z* walls of the liquid-hydrogen absorbers and perhaps by making the process more adiabatic, with less momentum swing. Other advantages for a gaseous absorber design include 1) a simple way to vary the *dE/dx* by changing the gas pressure or type for diagnostics or cooling optimization, 2) a possibility of a clear path down the center of the channel for optical or hadron-beam alignment, and 3) reduced radiation backgrounds for beam-diagnostic devices inside the channel. Disadvantages are related to the engineering challenges of RF cavities operating at low temperature and high pressure and to the vacuum window at each end of the channel.

Paschen's Law

Most RF cavities associated with particle accelerators operate in as good a vacuum as possible to avoid electrical breakdown. This is done so that ions that are accelerated by the high voltages in the RF cavity rarely encounter atoms of the low-pressure residual gas, and so the avalanche process of breakdown is inhibited. Other RF systems that do not require the ultrahigh vacuum of an accelerator typically suppress RF breakdown by using dense materials between electrodes. Ions passing through these materials, which include high-pressure and/or high-density gases, have such a short mean free path between collisions that they do not accelerate to energies high enough to create an avalanche. The relationship in the high-pressure regime between the electrical breakdown voltage and the pressure times gap width is known as Paschen's Law.[1] For gaseous hydrogen a more modern version is given by[2]

$$V_s = 0.448\,(nd) + 0.6\,(nd)^{1/2},$$

where V_s is the static breakdown voltage in kV, n is the number density of atoms or molecules in units of 10^{18} cm^{-3}, and d is the separation in cm.

While the exact value of a breakdown voltage will depend on many parameters, such as RF frequency, surface condition, and external magnetic field, we can use Paschen's Law as a first approximation. From this expression we see that above a pressure of about 40 atmospheres at room temperature, gradients in excess of 50 MV/m can be supported. Since density is the actual variable of merit for suppressing breakdown, a lower temperature and pressure can also be used for ease of engineering, since $n = PV/RT$. As we shall see, the density of hydrogen needed to provide the energy loss for ionization cooling is over twice that needed to suppress electrical breakdown.

Cooling-channel designs

The present baseline designs of ionization-cooling channels for a neutrino factory or muon collider are based on sets of RF accelerating cavities alternating with thin-walled flasks of liquid hydrogen as energy absorbers. This arrangement is well matched to a channel that has periodic low-β regions at which the beam is tightly focused, and these regions are where the liquid hydrogen (LH_2) absorbers should be placed to optimize ionization cooling. Other designs of cooling channels have recently been examined that are tightly focused by strong solenoids along their entire length. That is, the low-β region can be considered continuous along the cooling channel, even if there are places along the channel where the direction of the solenoidal field is reversed.

The proposal here, then, is to consider a rather simple structure for an ionization-cooling channel. It is a very long set of RF cavities filled with gaseous hydrogen or helium, with one pressure window before the first cavity and one pressure window after the last cavity. Superconducting solenoids are located between or surrounding the RF cavities.

The use of gaseous hydrogen or helium as a continuous energy absorber to match the continuous low β of the cooling channel involves many engineering tradeoffs. However, a number of tricky design issues now being confronted for cooling channels using RF cavities operating in vacuum and using discrete liquid-hydrogen absorbers can be solved or evaded by the approach advocated here. Some virtues and drawbacks of the proposed gaseous-absorber channel relative to one that uses liquid absorbers are discussed below.

Cooling improvements

The original motivation for a study of a gaseous energy absorber was to improve ionization-cooling efficiency by removing the windows of the flasks of liquid hydrogen used in the present designs and by providing a more adiabatic energy-loss process. Studies indicate that even the thinnest walls of metallic LH_2 containers degrade the cooling process, mostly by scattering muons out of the cooling channel. Additionally, by reducing the momentum variations of the muons in the channel, a continuous absorber could provide an advantage, either because of its more adiabatic nature or by possible improvements in the magnetic-channel lattice design.

Balbekov has done a preliminary study using a double-flip cooling channel comparing a gaseous absorber with the usual channel containing aluminum flasks filled with liquid hydrogen.[3] He finds that the final cooling emittances are reduced by about 15% by eliminating the aluminum absorber windows, and the number of muons per proton is increased by about 10%. This does not include the effects of scattering in the final vacuum window, which, in general, will depend on the pressure of the hydrogen gas; this is discussed further below.

Other benefits and drawbacks

There are many practical advantages of a cold gaseous absorber, which would be attractive even if ionization cooling were not improved. These include:

1) A way to eliminate the need for LH_2 chambers with ultra-thin walls.
2) A simple way to vary the energy loss by changing pressure or temperature. This could be used for diagnostics or cooling optimization, especially to compensate for RF variations due to cavity improvements or failures.
3) An ability to vary the absorber characteristics for diagnostics or optimization (e.g., compare observed performance with simulation predictions for H_2 vs. He or N_2).
4) A way to cool the Be windows or grids of the closed-cell RF cavities.
5) A means to reduce the background radiation that interferes with diagnostic devices in the channel.
6) A clear path down the center of the channel for optical alignment or hadron-beam diagnostics.
7) A "symbiotic" connection with the RF, allowing the cavities to operate at lower temperature to improve their electrical efficiency.

These benefits come at some price, of course:

1) The continuous absorber works best for cooling channels that have a more-or-less continuous low β.
2) With high-pressure, low-temperature components and hydrogen gas, it is an entirely different engineering problem than the standard cooling channel.
3) There are pressure windows not only at the two ends of the cooling channel but also at the RF interfaces between the cavities and the waveguides.

One possible configuration

To determine the operating parameters of a gaseous-absorber cooling channel, one can scale from the LH_2 design. Since we plan to use the same amount of RF, we can expect to use the same mass of hydrogen absorber. (To first order, either system is a similar safety concern as to amount of hydrogen). Gaseous Hydrogen (GH_2) at room temperature is about one thousandth the density of LH_2 (0.0838 g/l at 20 °C and 1 atm compared to 0.0708 g/cm^3 for liquid). Roughly speaking, present LH_2-channel designs have absorbers that occupy about one tenth of the length of the channel. Thus one can conclude that about 85 atmospheres of GH_2 are required. Note that this is well above the RF-breakdown pressure of hydrogen, which is near 44 atm.

Although this high pressure is possible, since there are examples of similar pressure vessels containing GH_2 even in HEP, a lower pressure would ease engineering problems. In fact, since the RF cavities could be in contact with the GH_2, one can cool both the cavities and the GH_2 to a low temperature. This provides an environment for more efficient RF operation, as well as the density needed for energy absorption at a lower pressure. The lower the pressure, the thinner the downstream pressure window can be, allowing us to minimize multiple Coulomb scattering as the beam exits the cooling channel. Two possible choices are 80 K at 23 atm, corresponding to a liquid-nitrogen coolant, or 30 K at 9 atm using a helium refrigerator. Hydrogen has a critical temperature of 33.2 K and critical pressure of 26.3 atm, so either of these choices is above the point of liquefaction. The actual choice should be made based on RF efficiency, window thickness, refrigeration economics, and structural-engineering tradeoffs.

The GH_2 in the ionization-cooling channel must be aggressively refrigerated and well circulated to remove the ionization energy lost by the beam and to cool the RF windows (made of Be sheets, rods, or tubes) used to improve the efficiency of the (closed-cell) RF cavities. The windows should be designed with holes for gas circulation, and with a clear path down the center of the channel for optical alignment and perhaps a diagnostic hadron beam. The use of hydrogen to provide cooling in a high-voltage environment is apparently common: as has been pointed out,[4] "Hydrogen gas is not a particularly good insulator (65% of air) from a breakdown voltage standpoint. Its very low viscosity and high thermal capacity make it an insulating gas of choice for high speed, high voltage machinery such as turbogenerators."

The relatively dense GH_2 should absorb much of the dark-current radiation within the cooling channel that has been of some concern for designers of beam diagnostics. Since the hydrogen density will be a factor of two above that needed to suppress RF-induced avalanches, additional ionization from the incident muon beam should also be absorbed. These are speculations, which require careful calculation and experimental verification.

The features of an ionization-cooling channel with a gaseous energy absorber may allow diagnostic devices other than those considered so far. Unfortunately, there is no Cherenkov radiation at our design energy from the muons, but there should be Cherenkov radiation from the decay electrons, which could be used to monitor the beam properties. The scintillation properties of hydrogen[5] may be useful, especially if a wave shifter can be added to the gas. The scintillation properties of helium could be used either in a diagnostic mode, as the absorber of choice, or as a dopant to the hydrogen. One can imagine special locations between the Be windows of adjacent RF cavities where profile monitors of thin metallic strips or wires could be placed. The monitors could work by secondary emission or by sampling the ionization of the GH_2 created by the muon beam.

Some engineering issues

The pressure windows at the ends of the channel are relatively straightforward. Simple physics considerations show that the thinnest pressure windows are hemispherical in shape, in which case the thickness t must satisfy

$$t \geq PR / 2S \, ,$$

where P is the pressure differential, R the vessel radius, and S the maximum allowable stress. The entrance window is likely to matter little since the beam emittance is large there. An estimate for the beam-pipe exit radius in the double-flip channel is R < 10 cm. If we assume 6061-T6 aluminum alloy and use the ASME[6] and Fermilab[7] standard safety factors of 4 with respect to the ultimate strength and 1.5 with respect to the yield strength of the window material, we find S = 72 MPa, and $t \geq$ 1.6 mm for 23-atm operation, or 6 mm for 85 atm. For a beam-pipe radius of 30 cm, the entrance window would need to be 3 times as thick. (These thicknesses could be proportionately reduced, perhaps by almost a factor of 2, if a stronger alloy such as 2090-T81 were used,[8] or by a factor of 2.8 in radiation lengths if AlBeMet were used, but further R&D is required to certify these materials for such applications.) We have here neglected some small effects that ASME includes in their standard,[6] but this is an approximate estimate that in any case needs to be backed up by finite-element analysis once a real implementation is being designed.

We can estimate the effect of scattering in the exit window on the final emittance using the heating term from the “Neuffer formula”:[9]

$$\Delta\varepsilon_n = \beta_\perp (14\ \mathrm{MeV})^2\, t \,/\, (2\,\beta^2 p_\mu m_\mu L_R)\ ,$$

where $\beta_\perp$ is the value of the transverse β function at the channel exit, $\beta = v/c$, and L_R = 8.9 cm is the radiation length of the window material (aluminum). Using Balbekov’s values[3] at the double-flip exit ($\beta_\perp \approx$ 10 cm, $p_\mu \approx$ 350 MeV), for t = 1.6 mm we find $\Delta\varepsilon_n \approx$ 0.005 mm·rad, a negligible effect given the exit emittance ε_n = 1.79 mm·rad.

The RF windows that provide the pressure barriers between the RF cavities and their power supplies are another concern. There may be an application in which this problem has been solved.

We conclude this section with a quote regarding safety:[4] “There isn't an explosion hazard, provided that the oxygen content in the hydrogen tank is kept below the flammable limit (around 5%). Of course, hydrogen has lots of other handling problems, including hydrogen embrittlement, it leaks through very tiny holes (even the pores in the metal tanks), and perfectly colorless, but very hot, flames.”

Next Steps

Many of the features of a gaseous energy absorber for ionization cooling of a muon beam have been investigated. The range of parameters for a cooling-channel design is within practical engineering limits. The use of hydrogen gas at liquid-nitrogen temperature (80K) and around 23 atmospheres pressure seems attractive. In this case, the RF cavities would also operate at the same temperature.

We suggest that two separate engineering designs could be investigated with cooling simulations in parallel. The first would be to incorporate closed-cell RF cavities with beryllium windows cooled by the circulating hydrogen gas. A second design would eliminate all “fragile” components (e.g. thin windows or tubes) by using open-cell cavities. If these are spaced such that strong solenoidal magnets of relatively small bore can be easily placed between the cavities, one might also reduce significantly the cost of the solenoids.

We also suggest beginning a program of experimental investigations into the behavior of high-pressure cold hydrogen gas in a cold RF cavity with external magnetic field and charged-particle radiation. This program would be to verify the statements found in the literature regarding high-voltage breakdown, establish our ability to address safety concerns, and develop beam-detection strategies. The new facility in the Linac parking lot seems like a perfect place for such a program.

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